4290

INSTRUCTIONS AND APPLICATIONS

Calibration Exciter Type 4290

A small electrodynamic vibration exciter designed for high-frequency calibration of piezo-electric vibration pick-ups. The built-in accelerometer allows complete control of the vibration level up to 30 kc/s. Especially well-suited for automatic recording of the frequency response of piezo-electric accelerometers.

- Accelerometers
- Acoustic Standing Wave Apparatus
- Artificial Ears
- Artificial Voices
- Audio Frequency Response Tracers
- Audio Frequency Spectrometers
- Audio Frequency Vacuum-Tube Voltmeters
- Automatic A. F. Response and Spectrum Recorders
- Automatic Vibration-Exciter Control Generators
- Band-Pass Filter Sets
- Beat Frequency Oscillators
- Complex Modulus Apparatus
- Condenser Microphones
- Deviation Bridges
- Distortion Measuring Bridges
- Frequency Analyzers
- Frequency Measuring Bridges
- Hearing Aid Test Apparatus
- Heterodyne Voltmeters
- Level Recorders
- Megohmmeters
- Microphone Accessories
- Microphone Amplifiers
- Microphone Calibration Apparatus
- Mobile Laboratories
- Noise Generators
- Noise Limit Indicators
- Pistonphones
- Polar Diagram Recorders
- Preamplifiers
- Precision Sound Level Meters
- Recording Paper
- Strain Gage Apparatus and Accessories
- Surface Roughness Meters
- Variable Frequency Rejection Filters
- VHF-Converters
- Vibration Pick-ups
- Vibration Pick-up Preamplifiers
- Wide Range Vacuum Tube Voltmeters

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Calibration Exciter

Type 4290

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Contents

Description 3
Frequency Characteristics 6
Operation 8
General 8
Relative Calibration of Accelerometers 10
Automatic Plotting of Accelerometer Frequency Response 10
Appendix 17
Absolute Calibration by the Reciprocity Method 17
Specifications 23
Part Numbers 24

Description

The Calibration Exciter Type 4290 (Fig. 1, 3) is a precision vibration exciter designed to vibrate accelerometers or small components at variable frequency in the range 50 Hz to 50 kHz. Due to this very extensive range, and because it gives reliable acceleration control up to 30 kHz, the Calibration Exciter is a highly useful reference device in high frequency vibration work. Its main application is the automatic plotting of the high frequency response of accelerometers, showing the first major resonance in most cases, in conjunction with the B & K Oscillators and Level Recorders. A further application which is of more special interest is the absolute calibration of accelerometers by the reciprocity method.

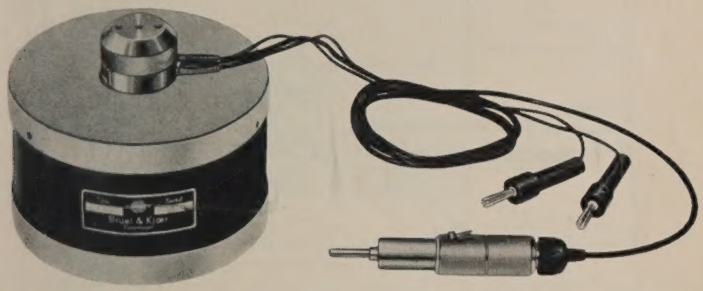

Fig. 1. Photo of the Calibration Exciter Type 4290.

The Exciter is of the electrodynamic type. It consists of two separate parts, a cylindrical permanent magnet and a small compact moving element. The top of the moving element (Fig. 2) which is smoothly machined, forms the vibrating table. Three ⅛″ W tapped holes (USA NC No. 5) are provided for the mounting of specimens.*) the small dimensions and the extreme compactness and rigidity of construction give the moving element an outstandingly high first resonance frequency (above 50 kHz). The whole vibrating unit is built in one block of nickel iron, non-magnetic alloy. The driving coil is wound on the metal structure and impregnated with a hard synthetic "Araldite" resin. Finally, axially built into the block is a small piezo-electric accelerometer, the

*) The screw thread in the more recent accelerometers is 10—32 NF., so in order to allow mounting to the moving element, a 10—32 NF to 1/8″ W converter is supplied with the 4290.

base of which is the vibrating table. This control accelerometer will follow exactly the movement of the table, and the output signal is used to control and monitor the acceleration at the table surface. The control accelerometer has a high "mounted" resonance frequency: around 65 kHz.
Due to its construction, the Calibration Exciter is very little affected by non-vibration environments and is therefore well-suited for use in environment-test chambers.*)
Electrical conductors for the control and drive power feed are also "built-in" and are so designed that they do not create disturbance throughout the frequency range. A plastic bag containing ten 1/8" W screws, one 1/8" W tap and an Allen Key is supplied with the instrument.

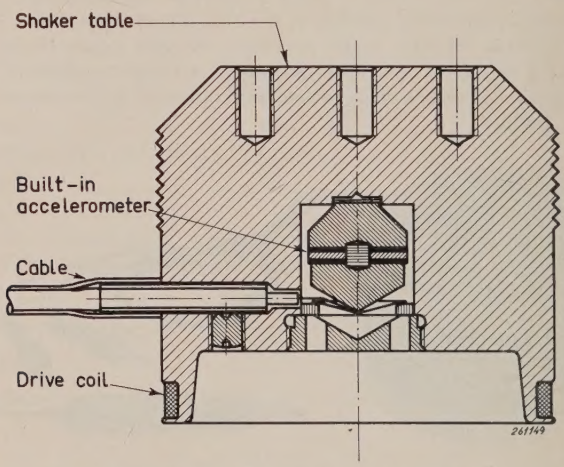

Fig. 2. Sectional view of the moving element.

When the moving element is placed onto the core of the permanent magnet, as shown in Fig. 3, the drive coil is situated in the radial magnetic field produced by the magnet. The suspension consists of a disc of foam nylon which is inserted between the moving element and the magnet core. This type of floating suspension, with no table restraint, is entirely satisfactory in the operating range of the Calibration Exciter and is free from transverse resonances. Since the magnetic field is practically uniform within the small air gap of the magnet, the fact that the moving element may not be exactly centered on the magnet axis has no influence, in so far that care is taken to ensure that the edge of the moving element does not come in contact with the flange of the magnets. The suspension resonance occurs at 30—50 Hz. Above

*) See also Specifications at the end of the manual.

this resonance, i.e. above approximately 100 Hz, the movement of the moving element is independent of the suspension. Assuming that the magnet has been placed on a horizontal table, and that the test objects center of gravity is located on the axis of the moving element, the movement of the vibrating table is rectilinear and vertical.*)

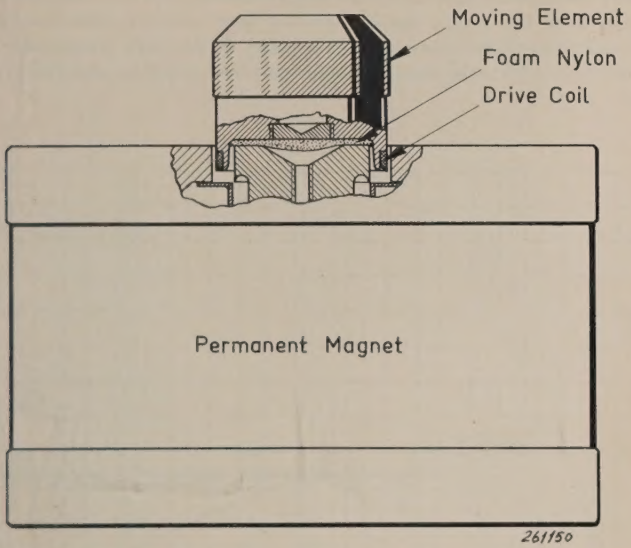

Fig. 3. Sketch showing the moving element and the suspension in place on the magnet.

The drive coil has a resistance of approximately 50 Ω and is designed to take a maximum continuous current of 240 mA r.m.s. corresponding to a maximum force output of about 2 Newton (i.e. approximately 0.2 kgf or 0.45 lbf). The mass of the moving element being of the order of 170 grammes, the maximum obtainable acceleration level is around 1 G r.m.s. when ordinary accelerometers or test objects with mass less than 30—60 grammes (1—2 oz.) are mounted. In general, calibration of piezo-electric accelerometers is carried out at much smaller levels, e.g. around 0.1 G, and a power supply of 12 V will be suitable for driving the Calibration Exciter throughout the frequency range. Piezo-electric transducers have an excellent dynamic linearity and calibration at a higher level would not give more exact information.

*) The Calibration Exciter Type 4290, however, is not designed for cross-axis sensitivity measurements.

Frequency Characteristics.

Typical acceleration level-versus-frequency curves for the Calibration Exciter are shown in Fig. 4. In the case **a,** the moving element is driven by a constant current, i.e. with an approximately constant force. The curve shows two resonance peaks, the first at very low frequencies (30 to 50 Hz) which is due to the suspension resonance and the second at ultra-audio frequencies (50 to 60 kHz) corresponding to the first major resonance of the moving element. Between these two peaks, the acceleration level remains approximately constant, but a slight decrease in level appears at the high frequencies due to the increase with frequency of eddy-currents electromechanical counteraction.

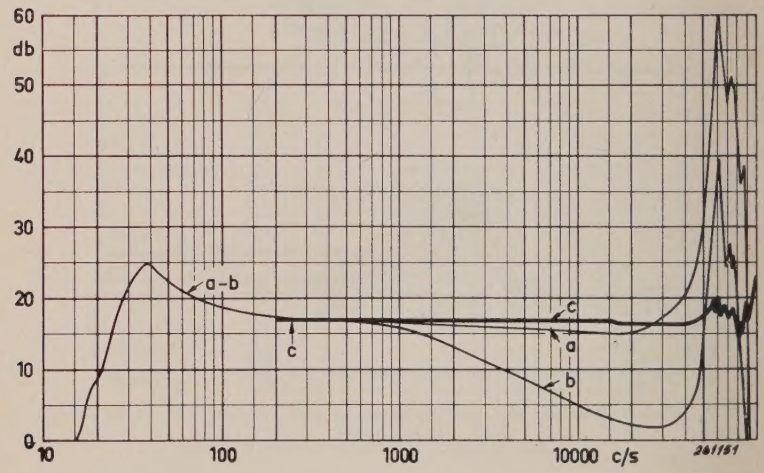

Fig. 4. Typical acceleration level versus frequency curves for the Calibration Exciter.

a) Exciter coil driven from a constant current source.
b) Exciter coil driven from a constant voltage source.
c) Exciter vibration controlled by the built-in control accelerometer.

When driving the Exciter from a constant voltage source, the current (and thus the exciting force and the resulting acceleration) decreases at high frequencies because of the increase in coil impedance and a characteristic of the type **b** is obtained.

Curce **c** shows the response of the Calibration Exciter when it is operated from a B & K Oscillator Type 1013 (frequency range: 200 Hz—200 kHz), the control accelerometer being connected through an amplifier to the compressor input of the oscillator (Fig. 7). A variation of the output from the control

accelerometer (i.e. of the acceleration level) will then modify the oscillator output until the preset vibration level is regained. Four different regulation speeds can be selected on the oscillator: 100, 200, 500 and 1ooo dB/sec. and the regulation accuracy is 1 to 2 dB for 45 dB original variation. These features ensure a constant acceleration level of the table throughout the frequency range 200 Hz—30 kHz and make the Calibration Exciter 4290 especially well-suited for automatic plotting of the high frequency response of modern accelerometers.

Note: Some more information about electrodynamic exciters characteristics will be found in the B & K Technical Review No. 3-1960.

Operation

General.

The Calibration Exciter should be used in an upright position. In cases where undesirable surrounding vibrations are present, their effects may be reduced by operating the Exciter in its case which is rubber-lined.

Power Supply.

The driving coil of the moving element is designed to be fed from the "12 V/60 Ω" output of one of the B & K Frequency Oscillators having a nominal power output of around 2.5 watts. The B.F.O. Type 1013 with the frequency range 200 Hz to 200 kHz will in most cases be preferred,*) since accelerometers rarely present irregularities below 200 Hz, and in general the investigations carried out with the Calibration Exciter are made towards the high end of accelerometer's frequency responses.

In practice, a voltage of a few volts corresponding to a power of a fraction of a watt is sufficient to drive the Calibration Exciter under normal conditions. The variation of the coil's impedance with frequency is represented in Fig. 5. The maximum voltage to be applied between terminals which corresponds to the maximum current of 0.25 A, varies in the same way and

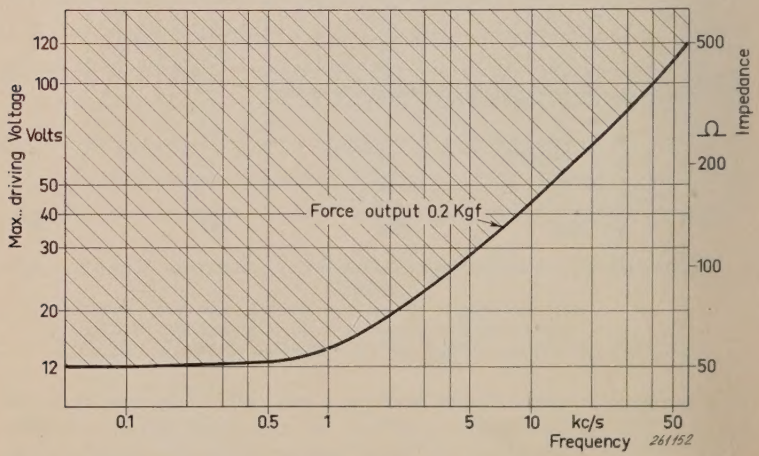

Fig. 5. Curve showing the variation with frequency of the impedance of the drive coil, and of the maximum drive voltage corresponding to a current of 0.24 A.

*) The other B & K B.F.O., Types 1022 and 1017, are of the same design as Type 1013 but with frequency ranges 20—20000 Hz and 2—2000 Hz respectively.

can be read from the figure. To evaluate the force output obtained with a certain voltage at a given frequency, it can be borne in mind that the force is approximately proportional to the driving voltage, the ratio being found from the maximum voltage point on the curve which corresponds to a force of about 0.2 kgf (200000 dynes).

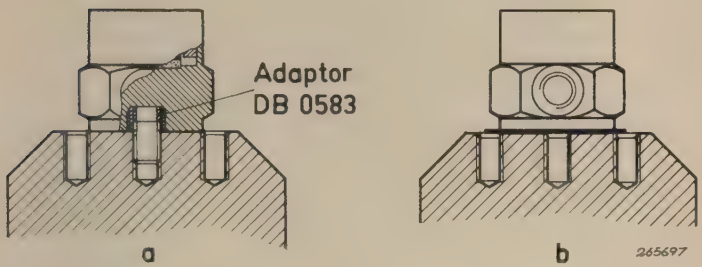

Fig. 6. Mounting of the accelerometer.
a) Stud mounting by means of a 1/8" W screw.
b) Adhesive mounting.

Mounting the Test Specimen.

Proper mounting is of great importance. To guarantee rectilinear motion, the test specimen should be centered on the moving element so that its center of gravity lies on the axis of the moving element, ensuring that the driving force is applied to the center of gravity of the assembly.

Different mounting techniques are possible (Fig. 6):

a) *Stud mounting*, by means of the 1/8" W screws supplied with the Exciter. The contact surfaces should be cleaned and "lubricated" with a little grease or wax, or joined by a thin lead washer, in order to obtain the stiffest possible connection and thereby the best high frequency response. A rather high mounting torque (max. 0.25 mkg) is recommended. (Do not press fingers against connection cables). Care should be taken that the studbolt is equally divided and engaged in the vibrating element and in the test accelerometer's base,*) and also that the surfaces of accelerometer and element make close contact.

*) In the case of the more recent accelerometers which have a 10—32 NF screw thread, the converter (part No. DB 0583) must be screwed into the base of the accelerometer in order to reduce the thread size to 1/8" W.

b) *Adhesive mounting,* by means of a little wax or thick grease, or double-backed tape. These techniques are simple, but less reliable at high frequencies than stud mounting.

In general, a technique corresponding to normal use of the accelerometer should be selected.

The moving element should not be kept continuously in place on the magnet. When the foam nylon is left compressed for a long period of time, a decrease of its compliance appears which causes a rise in the suspension resonance frequency to above 50 Hz. Normal conditions are regained by simply releasing the suspension for a few minutes.

During measurements, the edge of the moving element should not touch the magnet flange as this may cause irregularities to appear in the results.

Relative Calibration of an Accelerometer at Fixed Frequency.

The unknown accelerometer is properly mounted on the vibrating element as described above. The Calibration Exciter should be driven by a current of 20 to 240 mA from a suitable generator at the chosen frequency. The output voltage from the test accelerometer is then compared to the output voltage from the control accelerometer by means of a vacuum-tube voltmeter. The voltage difference in dB is then equal to the ratio in dB between the respective sensitivities of the accelerometers, and the unknown sensitivity can be calculated in mV/G from the value of the control accelerometer sensitivity which is given on the individual calibration chart. This value is constant within $\pm$ 1 dB throughout the audio-frequency range, but it should be noted that the sensitivity of the control accelerometer increases slightly at high frequencies due to the approach of its resonance: at 20 kHz the sensitivity is for this reason about 1 dB higher and at 30 kHz around 2 dB higher than the calibration sensitivity, which is measured at 50 Hz.

The output voltage from the control accelerometer should be measured with an instrument having an input impedance which is high in comparison to the accelerometer impedance. If necessary, a correction which is calculated from the complex impedance ratio should be added to the reading. At high frequencies the impedance ratio is normally equal to the ratio between the input capacity of the voltmeter and the capacity of the accelerometer.

Automatic Plotting of the Frequency Response of Accelerometers.

As mentioned in the "Description" and shown in Fig. 4 curve c, it is possible to operate the Calibration Exciter with a flat frequency characteristic in the range 200 Hz to 30 kHz from a B.F.O. Type 1013. Plotting the frequency response of a test accelerometer is then simply made by recording the output level of the accelerometer while varying the frequency of the B.F.O.

The Brüel & Kjær Level Recorder Type 2305 (frequency range 2 Hz –200 kHz) is especially designed for the automatic recording of frequency response characteristics when combined with the B & K Beat Frequency Oscillators.

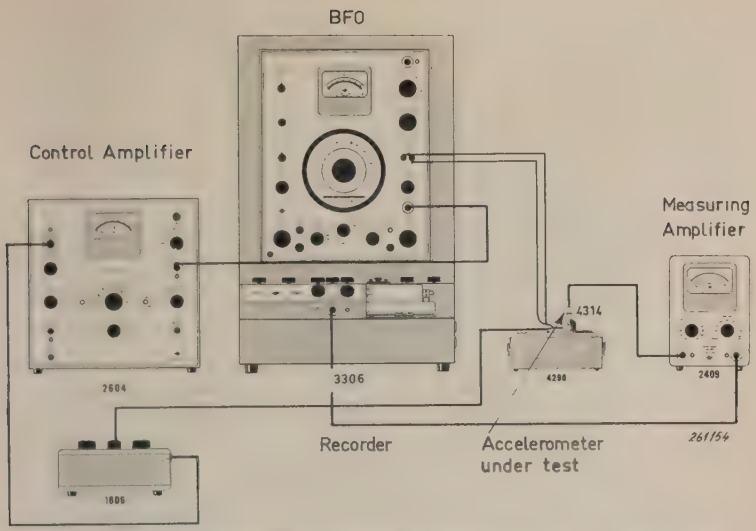

Fig. 7. Set-up for automatic recording from 200 Hz to 30 kHz of the frequency response of an Accelerometer Type 4314.

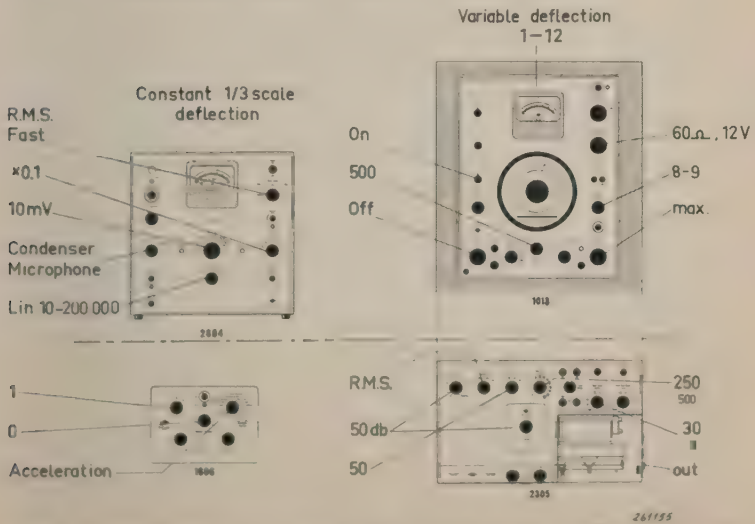

Fig. 8. Typical final adjustments of the control and recording instruments in Fig. 7.

Mechanical coupling between the frequency dial of the BFO and the paper drive of the Recorder enables automatic scanning and recording on pre-calibrated paper, the frequency graduations of which correspond to the logarithmic frequency scale of the BFO. Six different dynamic ranges are available on the Recorder by interchanging the range potentiometer: Logarithmic 10, 25, 50 or 75 dB and linear 10—35 or 10—110. The BFO and the Recorder are also available in one combined unit called the Automatic Frequency Response Recorder.

A typical measuring set-up with the Automatic Frequency Response Recorder Type 3306 grouping a B.F.O. 1013 and a Level Recorder 2305 is illustrated in Fig. 7.

The Calibration Exciter drive coil is operated from the 12 V—60 Ω load output of the BFO. Under these conditions no overload of the coil is possible even at the lowest frequencies, and a very convenient constant acceleration level of about 0.1 G is obtained. As the Compressor input of the BFO requires a voltage of at least 1 Volt across 100 kΩ and as the zero level on the Level Recorder corresponds to an input of approximately 5 mV across 18 kΩ at maximum sensitivity, the output signals from the control accelerometer and the test accelerometer have to be amplified. The choice of amplifiers should take into account both the amplification range required and the frequency range of interest. The lower limiting frequency is approximately inversely proportional to the capacity of the accelerometer connected at the input. The characteristics of the different Brüel & Kjær amplifiers or amplifier combinations which may be of interest are listed in the following table in order to facilitate the proper choice of instruments.

Instrument Type Numbers	2409	2410	2604	2604 + 2612	2604 + 1606[1])	1606[2]) + 2801	2603 or 2107 or 2112
Max. Amplification	60 dB	60 dB	100 dB	100 dB	100 db	20 dB	100 dB
Noise Level (with 500 pF on the input)	20—30 μV	40 μV	15—20 μV	15—20 μV	15—20 μV	5—10 μV	10—15 μV
Imput Impedance Resistance Parallel capacity	10 MΩ 20 pF	1.5 MΩ 15—20 pF	1.1 MΩ 30 pF	270 MΩ 3 pF	200 MΩ 50 pF	200 MΩ 50 pF	2.2 MΩ[3]) 30 pF
Higher Limiting Frequency of the Amplifier	200 kHz	50 kHz	200 kHz	200 kHz	100 kHz	40 kHz	45 kHz

[1]) Type 1606 adjusted to minimum amplification.
[2]) Type 1606 adjusted to 20 dB amplification.
[3]) Types 1606 or 2612 can also be connected to Types 2603—2107—2112 in order to increase the input impedance.

Control Amplifier. Since the signal from the control accelerometer is of the order 0.5 mV it has to be amplified by about 70 dB. An Amplifier Type 2603 or 2604 or 2112 may be used. As the capacity of the control accelerometer is 500—700 pF, the low frequency response of the amplifier begins in some cases to drop off at 200 Hz, and this could affect the regulation characteristic at its commencement. It is therefore advisable to insert a preamplifier with high input impedance such as the Cathode Follower 2612 or the Vibration Pick-up Preamplifier 1606. The *Vibration Pick-up Preamplifier Type 1606* is especially designed for vibration measurement and it has been preferred for the practical example in Fig. 7. Type 1606 is provided with integrating circuits allowing the measurements of velocity and displacement and includes a small vibration table powered from the mains for sensitivity checking of vibration pick-ups by the "chatter" technique.

Measuring Amplifier. The choice of the measuring amplifier depends on the characteristics of the test accelerometer and of the frequency range of interest. In the case of the B & K Accelerometers, which have a rather high sensitivity, the Electronic Voltmeter Type 2409 can be used as Amplifier (Fig. 7). It must be ascertained, however, that the low frequency cut-off of the input circuit is sufficiently low. The 3 dB cut-off frequency (f_c) of the equivalent RC network representing the input circuit is readily calculated from the formula:

$$f_c = \frac{1}{2 \pi R C}$$

where R is the resultant resistance (including the leakage resistance of the accelerometer) and C the resultant capacity of the input circuit. In the case of the set-up of Fig. 7, the total capacity is 1000 + 20 = 1020 pF and the resulting resistance practically 10 MΩ (refer to 2409 characteristics in the table above), since the leakage resistance of the accelerometer Type 4314 including cable is more than 200 MΩ. Then, in this particular case, f_c is around 16 Hz. The 1 dB drop which is about one octave higher would occur at 32 Hz. In the case of an accelerometer Type 4312 or 4313 having a capacity of around 500 pF, the cut-off frequency would be twice as great but it is seen that in both cases the cut-off is far below the minimum frequency of the test 200 Hz).

Finally it should be noted that if the low frequency cut-off in the measuring circuit is slightly too high, the consequent error in the recording can be compensated for by giving the control circuit exactly the same low frequency cut-off, and vice versa. This method can, in certain cases, dispense with the use of a preamplifier at the expense of the exact adjustment of the cut-off characteristics in one of the circuits by means of a variable resistance.

Recording of the Control Signal.

After a satisfactory plot of the accelerometer frequency response has been obtained it is advisable to make on the same chart a recording of the control signal in order to check the constancy of the acceleration level with varying

frequency. This is readily made by returning to the starting point with help of the "reverse" motor switch on the Recorder and then connecting the measuring amplifier to the control circuit instead of the tested accelerometer (without disconnecting the compressor). The Control Amplifier and the Oscillator keeping their previous adjustments, recording of the acceleration versus frequency curve is made automatically in the same way as the accelerometer frequency response was plotted. See item 11 in the following practical procedure.

Possible irregularities of the control signal curve and the small increase at high frequency of the control accelerometer sensitivity can then be taken into account for accurate determination of the acceleration level. See Fig. 9.

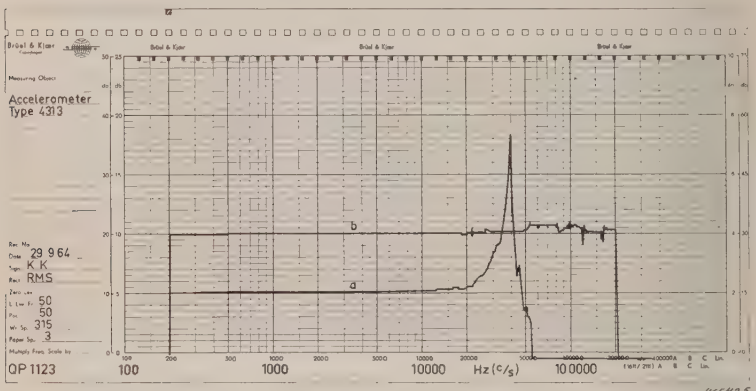

Fig. 9. Frequency response obtained with the set-up of Fig. 7.
(a) Accelerometer response.
(b) Signal from control accelerometer.

Practical Operation Procedure Corresponding to the Set-up of Fig. 7.

1. Make sure that all the instruments are adjusted to line voltage.
2. *Adjustment of the BFO.* Before connecting up the measuring arrangement, the BFO should be frequency calibrated as described in its Instruction Manual. Set OUTPUT VOLTAGE to zero after adjustment and set MATCHING IMPEDANCE to 60 Ω / 12 V and COMPRESSOR SPEED to 500 dB/sec.
3. *Adjustments of the Recorder.*
   During adjustment, lift the writing pen.
   The Recorder is normally equipped with a 50 dB potentiometer. This will provide a suitable dynamic range for recording the resonance peak of most piezo-electric accelerometers. In cases where a more detailed investigation of parts of the frequency characteristic of an accelerometer is

wanted, a 25 dB or a 10 dB potentiometer could be used, and the knob POTENTIOMETER RANGE dB shifted to the corresponding position.

The writing speed in dB/sec. should be smaller than the compressor speed of the B.F.O. On the other hand, it should be high enough with respect to the frequency scanning speed to ensure accurate recording of all variations in the response of the test accelerometer.

The Recorder may be used in "Single Chart" recording position (side lever X out, Single Chart pushbutton up and STOP/START switch on "Start").

Finally the RMS rectifier and a Lower Limiting Frequency of 20 or 50 Hz should be selected as shown in Fig. 8.

4. Connect the apparatus as shown in Fig. 7.
5. Make adjustments to the control amplifier Type 2604 and preamplifier Type 1606 as indicated in Fig. 8.
6. *Adjustment of the Vibration Level.* The B.F.O. being adjusted to 200 Hz, set COMPRESSOR VOLTAGE and OUTPUT VOLTAGE to maximum and then turn the knob COMPRESSOR VOLTAGE counterclockwise until the meter of the B.F.O. indicates 1 to 1.5 Volts. Temporarily switching out the clutch of the B.F.O., sweep manually the frequency range 200 Hz – 30 kHz and check that the maximum deflection on the B.F.O. meter does not exceed 12 Volts, if it does, turn COMPRESSOR VOLTAGE clockwise. The deflection of Type 2604 meter should remain around 3 – 4 on the upper scale.
7. *Measuring Amplifier.* In the case of Fig. 7, where the accelerometer being frequency calibrated is the B & K Type 4314, the Electronic Voltmeter Type 2409 should be set to "0.1 V" and "RMS - V.U. Damping". In general, the sensitivity of the measuring amplifier should be adjusted in order to avoid overdriving when the accelerometer comes into resonance or at any maximum sensitivity point in the frequency sweep.
8. Reset the B.F.O. frequency dial pointer to 200 Hz and clutch on.
9. By means of the INPUT POTENTIOMETER and ATTENUATOR of the Recorder give the stylus a few dB deflection. Move the paper until the 20 Hz line is just under the pen (the frequency scale is to be multiplied by a factor 10). Lower the pen.
10. Start the automatic recording by pressing the "Single Chart" push button for a few seconds. The scanning will automatically stop after a complete revolution on the BFO.*)
11. *Recording of the Control Signal.*
    a. With the help of the Reverse switch on the Recorder, move the paper back to the starting point.

*) Since the sensitivity of the control accelerometer is only constant up to 30 kHz, the higher part of the recording should not be taken into consideration.

b. Disconnect the test accelerometer from the Measuring Amplifier input and connect instead the EXTERNAL FILTER INPUT of the Control Amplifier Type 2604 to the Measuring Amplifier input by means of a screened cable.
c. Adjust the sensitivity of the measuring amplifier until its meter indicates a convenient deflection. Adjust the sensitivity of the Recorder by means of the input potentiometer and attenuator in order to situate the control signal recording at a convenient position with respect to the recorded frequency response (see Fig. 9).
d. Without altering the other parameters in the set-up, start recording as under item 10.

Remarks.

If undesirable irregularities appear on the recordings, check the mounting of the Calibration Exciter and check the frequency response of the measuring and control circuits by means of the BFO.

In a permanent measuring set-up the control amplifier meter may be directly calibrated in acceleration level units by making a voltage calibration of Type 1606 + Type 2604 by means of the BFO, and dividing the voltage values by the sensitivity of the control accelerometer. Then, by measuring the output voltage of the test accelerometer and the acceleration level on the control amplifier the frequency response recording can be calibrated in mV/G sensitivity.

Appendix

Reciprocity Calibration of Piezoelectric Accelerometers.

Measurement of the sensitivity of an accelerometer can usually be made by direct comparison with the built-in control accelerometer of the Calibration Exciter as described in the paragraph "Relative Calibration of Accelerometers". The accuracy of such a determination, however, will not normally be better than ± 1 dB. If a better accuracy is wanted, or when it is required to check the sensitivity of the control accelerometer at high frequencies, an absolute calibration of both the unknown and the control accelerometer can be made by means of the reciprocity method. This method, which does not require that the amplitude of the motion is determined, allows a precision of the order of ± 0.5 dB to be obtained by means of the Calibration Exciter and B & K electronic equipment.

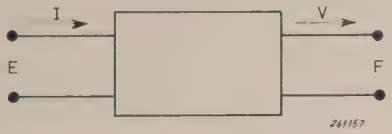

Fig. 10. Quadripole representation of an accelerometer.

The reciprocity method of calibration is based upon the fact that generally a reciprocal correspondence exists between input and output of transducers which are reversible, passive and linear. Piezoelectric accelerometers such as the B & K accelerometers fulfil these requirements and are reciprocal.
Consider a linear electromechanical transducer as a quadripole (Fig. 10) the general equations of which are:

$$E = z_{ee}\, I + z_{em}\, V \qquad (1)$$
$$F = z_{me}\, I + z_{mm}\, V, \qquad (2)$$

where E, I, V, F are the voltage, current, velocity and force and z_{ee} etc. are constant coefficients. Reciprocity is expressed by:

$$z_{em} = \pm\, z_{me}$$

When making I = 0 in (1) it is seen that z_{em} is the velocity sensitivity of the transducer:

$$z_{em} = \frac{E\ (I = 0)}{V}$$

Similarly, z_{ee} is the electrical impedance between terminals of the transducer when it is blocked (V = 0) and z_{mm} is equal to the ratio $\frac{F}{V}$ for I = 0.

Applying these considerations to a piezoelectric accelerometer excited sinus-

oidally with an angular frequency ω leads to the following simultaneous equations, when operating below the resonant frequency region:*)

$$E = I/j\,C\,\omega + j\,\omega\,S\,V \quad (3)$$
$$F = j\,\omega\,S\,I + j\,\omega\,m\,V \quad (4)$$

S being the sensitivity (unloaded output voltage/acceleration), m the mass, and C the capacity between terminals of the accelerometer.

Reciprocity calibration of a piezoelectric accelerometer carried out with the Calibration Exciter will firstly consist of measuring the ratio between the sensitivities of the unknown accelerometer and the control accelerometer, and secondly determining the product of sensitivities by means of a reciprocal test where the test accelerometer is fed by a known voltage. The reciprocal test is shown schematically in Fig. 11.

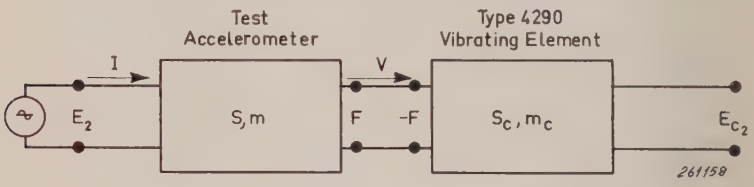

Fig. 11. Block-diagram of a reciprocity measurement.

As the two accelerometers are fastened together, they have the same speed V. The resulting force acting on the system is equal to zero. Assuming that the electrical consumption at E_{c_2} terminals is negligible ($I_2 = 0$) and calling S, m, Sc, m_c the sensitivities and masses of the accelerometers, the general relations (3,4) give by application to each accelerometer:

$$E_2 = I/j\,C\,\omega + j\,\omega\,S\,V \quad (5)$$
$$F = j\,\omega\,S\,I + j\,\omega\,m\,V \quad (6)$$
$$E_{c_2} = j\,\omega\,Sc\,V \quad (7)$$
$$-F = j\,\omega\,m_c\,V \quad (8)$$

From (6, 8) follows:

$$-I = \frac{m + m_c}{S}\,V = \frac{MV}{S}$$

by calling M the total mass of the vibrating system.

Then from (5, 7) is derived:

$$\frac{E_2}{E_{c_2}} = \frac{S}{S_c} + \frac{M}{S\,S_c\,C\,\omega^2} \quad (9)$$

Thus, by knowing the capacity C of the driving accelerometer, the total mass

*) For extension of the equations for wave effects around and above the natural frequency the reader is referred to:

1. M. HARRISON, A. O. SYKES, P. G. MARCOTTE, "The Reciprocity Calibration of Piezoelectric Accelerometers", J.A.S.A., Vol. 24, No. 4, July 1952.
2. AMERICAN STANDARDS ASSOCIATIONS, Calibration of Shock and Vibration Pick ups. S 2. 2.-1959.

and the frequency, and by measuring the voltage ratios

$$r_1 = \frac{E_1}{E_{e1}} = \frac{S}{S_e} \text{ and } r_2 = \frac{E_2}{E_{e2}} \tag{10}$$

the value of the sensitivities S and Sc can be determined. See Fig. 12.
In most cases E_2/E_{e2} will be a large number and S/S_e can be neglected in equation (9) (in the case of B & K accelerometers the relative importance of S/S_e is less than 1 %), and the following formulae transcribed from (9, 10) are to be employed:

$$r_1 = \frac{S}{S_e} \qquad r_2 = \frac{M}{S\,S_e\,C\,\omega^2}$$

leading immediately to:

$$S = \frac{1}{\omega}\sqrt{\frac{r_1}{r_2}} \times \frac{M}{C} \qquad S_e = \frac{S}{r_1} \tag{11}$$

By using the MKS system of units, the sensitivity is obtained in volts/m sec^{-2}. With practical units, calling f the frequency in Hz, the expression of S related to the "standard" acceleration of gravity ($G = 9.81$ m sec^{-2}) becomes:

$$S\ (\text{mV/G}) = \frac{4.93 \times 10^7}{f\ (\text{c/s})} \times \sqrt{\frac{r_1}{r_2}} \times \sqrt{\frac{M\ (\text{grammes})}{C\ (\text{pF})}} \tag{12}$$

Measuring Set-up.

Although the following description involves only Brüel & Kjær equipment, the calibration procedure would be identical using any other equipment featuring similar characteristics. The measuring set-up is shown in Fig. 12. A Beat Frequency Oscillator Type 1013 is used as a generator for feeding the Calibration Exciter Type 4290 in the first test and energizing the accelerometer in the reciprocal test.

The voltage ratios are measured by means of a Vibration Pick-up Preamplifier Type 1606 connected to a Spectrometer Type 2111 or 2112. A Cathode Follower Type 2612 (with input adaptor) can also be used instead of Type 1606 as a link between the accelerometers and the Spectrometer. In the reciprocal test (Fig. 12b) the permanent magnet and the coil of the Calibration Exciter are not in use and the vibrating block should simply be placed upon a soft surface (e.g. inside the cover of Type 4290's case).

Measurement of E_{e2} has to be carried out selectively in order to obtain a good signal-to-noise ratio. The Spectrometer enables accurate selective measurements of voltages down to 0.1 mV at full deflection and allows the check of distortion percentages to be carried out very easily. The attenuation produced by the filters is 50 dB at $\pm$ 1 octave of the center frequency.

The frequency range in which reciprocity calibration is feasible is limited at low frequencies by the noise level of the measuring set-up and the maximum

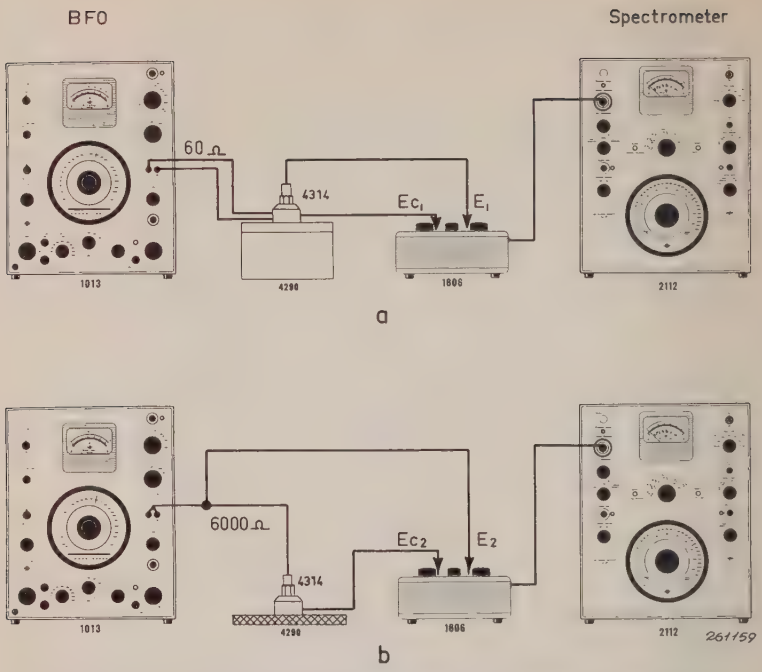

Fig. 12. Measuring set-up for the two phases of a reciprocity calibration.

a) Measurement of $r_1 = \dfrac{E_1}{E_{c_1}} = \dfrac{S}{S_c}$

b) Measurement of $r_9 = \dfrac{E_2}{E_{c_2}} = \dfrac{M}{S\,S_c\;C\;\omega^2}$

available value of the driving voltage E_2. The BFO Type 1013 has a maximum output voltage of 120 V r.m.s. which would not damage the accelerometer but the best conditions for the reciprocal test are realized by using a voltage of 30 to 60 V r.m.s. in the 120 V range in order to keep the distortion from the generator as low as possible. To be able to apply the equations 11—12, the maximum test frequency should be well below the first major resonant frequency of the driving accelerometer or of the moving element of the Type 4290. With the different B & K accelerometers the limits are approximately as follows:

Type 4332: 1 kHz to 10—15 kHz
Type 4333: 2.5 kHz to 20—30 kHz
Type 4334: 0.5 kHz to 10—15 kHz
Type 4335: 1 kHz to 20—30 kHz

Practical Measurements.

The accuracy of the reciprocity calibration is greatly dependent upon the care taken in the measurements. The following hints, which refer to the operation of the set-up of Fig. 12, should also be kept in mind when using other instrumentation.

1. *The mounting of the test accelerometer* is made with maximum care according to the technique described in "Operation". If it is intended to make a reciprocity calibration at frequencies lower than 2 kHz, it is recommended to insert the mica washer or the cable holder between the contact surfaces so as to reduce the influence of small mechanical deformations in the vibrating table which could be non-negligible due to the very low acceleration level in the reciprocal test.

2. The measurements of the voltage ratios should be made by measuring *on the same instrument* the difference in dB between the two quantities involved. In this way no voltage calibration of the instruments is necessary. Before a reading is taken it should always be checked that the signal-to-noise ratio is satisfactory (by using OSCILLATOR STOP pushbutton on the B.F.O.).

3. Since the formulae to be employed involve unloaded output voltages, corrections should be made to the readings if the input impedance (general capacitive at high frequency) of the measuring instrument is not high enough to be neglected. This is the situation in the set-up of Fig. 12, where Type 1606 is used on Attenuation 1 and with only a few dB amplification and presents an input capacity of approximately 30 pF. Assimilating 1 dB to 10 % the correction, which normally is only a fraction of dB, is readily found as:

$$\Delta r_1\,(\mathrm{dB}) = 10 \times \left(\frac{30\ \mathrm{pF}}{C\ (\mathrm{pF})} - \frac{30\ \mathrm{pF}}{C_e\ (\mathrm{pF})} \right)$$

C = capacity of test accelerometer
C_e = capacity of built-in accelerometer

which is to be added to the value of r_1 read in dB, and the correction to be added to r_2 is

$$\Delta r_2\,(\mathrm{dB}) = \frac{10 \times 30\ \mathrm{pF}}{C_e\ (\mathrm{pF})}$$

4. In the measurement of E_2, in order to avoid overdriving, the Spectrometer's METER RANGE switch should be set to 10 V and the Preamplifier Type 1606 should be used with Attenuation 10^2. It is, furthermore advisable to compare the 40 dB step of the Type 1606 attenuator to the total attenuation of the Spectrometer's RANGE MULTIPLIER attenuator, this being the most accurate in the set up (max. error $\pm$ 0.2 dB in the entire frequency range) and to take account of any difference in the evaluation of r_2. By these precautions r_2 can be determined with an accuracy of about $\pm$ 0.5 dB.

5. The measurement of M is made simply by weighting the vibrating block (weight is in the order of 160—180 g plus 20—30 g for the accelerometer). The cables should be held so that they are horizontal where they join the block. In this position, the error from the cables weight is less than 1 %. Finally the value of C, in the case of B & K accelerometers, will be found on the individual calibration chart with a precision of a few pF.

Numerical Example and Accuracy.

Accelerometer Type 4315. Test frequency 5 kHz (± 0.1 %).

$C = 1080$ pF, $C_e = 614$ pF.

$\Delta r_1 = -0.2$ dB $\quad r_1 = 7.1 \pm 0.2$ dB

$\Delta r_2 = -0.5$ dB $\quad r_2 = 105.7 \pm 0.7$ dB

$M = 182 \pm 1$ grammes

$$\sqrt{\frac{r_1}{r_2}} = -49.3 \pm 0.45 \text{ dB} = 0.00345 \pm 5\ \%$$

$$\sqrt{\frac{M}{C}} = 0.409 \pm 0.5\ \%$$

$S = 13.9$ mV/G ± 6 %

$S_e = 6.15$ mV/G ± 6 %

The probable accuracy (standard error) is 3 %.

Remark. The same results would be obtained by employing the control accelerometer as the energizing accelerometer in the reciprocal test instead of the test accelerometer, provided that a corresponding permutation of the involved quantities is made in the formulae.

Specifications

General.

Frequency Range: 50 Hz—50 kHz.
Frequency Characteristics:
Servo-controlled with B.F.O. Type 1022: Linear within + 1 / —1.5 dB from 100 Hz to 20 kHz.
Servo-controlled with B.F.O. Type 1013: Linear within + 1 / —3 dB from 200 Hz to 30 kHz.
Maximum Force Output: 2 Newton = o.2 kgf = o.45 lb (r.m.s.).
Moving Element Mass: 150—180 g.
Maximum Acceleration (unloaded): 1.1 G r.m.s.
Suspension Resonance: 30—50 Hz.
First Major Resonance of Moving Element: 50—60 kHz.
Distortion (sinusoidal input): Less than 1 % from 200 to 20ooo Hz.
Stray Field on Vibrating Table: 50—100 Gauss.

Drive Coil.

Maximum Continuous Current: o.24 A (r.m.s.).
Resistance: Approximately 50 Ω.
Inductance: 2—5 mH (dependent upon frequency).
Max. Continuous Power Dissipation: 3 W.
Winding: 230 turns.

Control Accelerometer.

Transducing Element: Lead-zirconium titanate.
Sensitivity: 5—7 mV/G*).
Capacity (incl. cable): 500—700 pF*).
Leakage Resistance: Greater than 500 MΩ*).
Natural Frequency: 60—70 kHz.
Voltage Temperature Coefficient: App. —o.1 % per °C between 0 and 100°C.

Environments.

Temperature: 0—80°C (32—176°F).
Humidity: 0—100 %.

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*) See individual calibration chart.

Overall Dimensions.

	Diameter	Height	Weight
Moving Element:	34 mm (1 11/32″)	30 mm (1 3/16″)	0.18 kg (0.4 lb)
Permanent Magnet:	113 mm (4 1/2″)	73 mm (3″)	4 kg (9 lb)
Length of cables:	Screened cable: 90 cm (3 feet)		
	Power cables: 50 cm (1 f. 8″)		
Wooden case:	230 × 160 × 120 mm		
	9 × 6 1/2 × 4 3/4 inches		

Accessories.

One 1/8″ W tap and ten 1/8″ W screws with one suitable Allen Key.
One 10—32 NF to 1/8″ W converter (Part Number DB 0583).

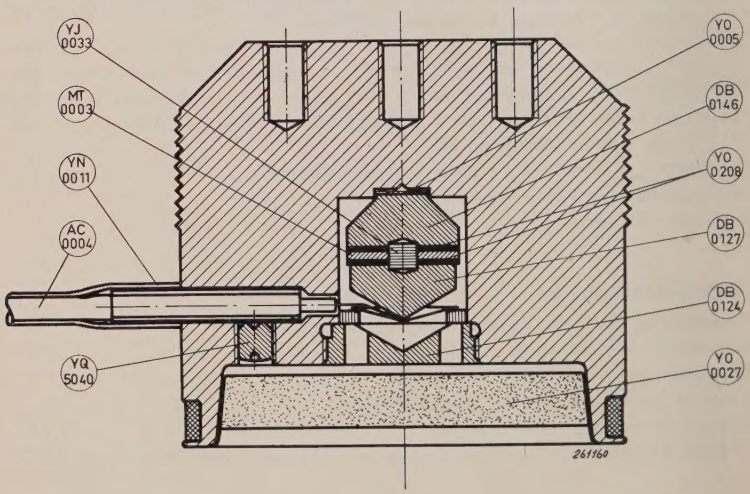
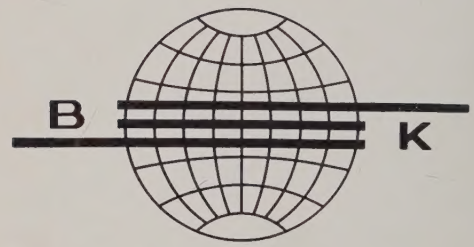


Fig. 13. Part Numbers.



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